# *Fabrication and Characterization of a Micro Turbine/Bearing Rig*

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## Abstract

This paper reports on a process to build, package, and instrument a 5-level wafer-bonded micro-machined turbine/bearing rig. The process flow involves the use of 5 wafers, 16 masks, and 9 deep silicon etching steps, as well as utilizing aligned wafer bonding, double-sided deep reactive ion etching (DRIE), and Laser-Assisted-Etching (LAE). This paper also shows experimental results on flow characteristics of the hydrostatic thrust bearings and the preliminary rotational performance of the device.

## Introduction

The first major fabrication challenge of realizing a miniature gas turbine generator is to demonstrate a baseline process capable of integrating the turbine rotor, bearings, and gas interconnects into a small package [1] [2]. This structure, called the micro-bearing rig, not only validates a process methodology for fabrication of freely-rotating high aspect ratio devices, but it is also a vehicle for research into critical micro air bearing stability issues.

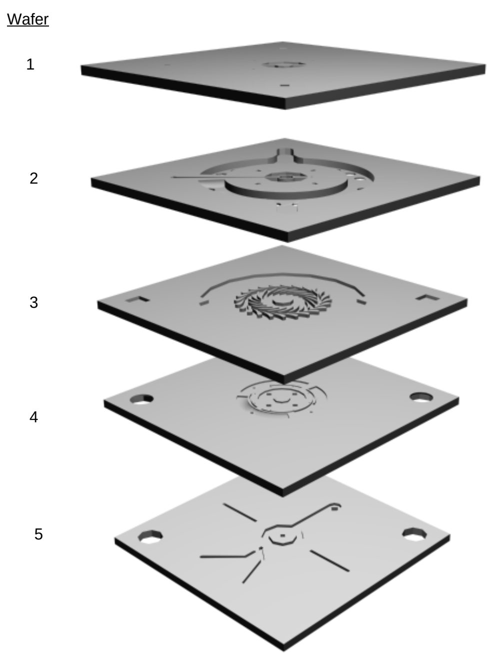


Figure 1 Exploded view of the micro bearing rig. The five layers are: 1. Forward foundation plate (FFP), 2. Forward endplate (FEP), 3. Rotor plate (RP), 4. Aft endplate (AEP), and 5. Aft foundation plate (AFP).

An exploded view of the device is shown in figure 1. The turbine rotor, located in the 3rd wafer, is supported by two different air bearings. (Fig. 2) Two pairs of wafers which cap the center wafer from both sides provide the pair of hydrostatic thrust bearings that support the rotor axially. Each hydrostatic thrust bearing has eight flow restrictors that provide the required pressure compensation. Externally pressurized nitrogen is brought in through these restrictors and flows through the bearing gap only a few microns wide. A self-pressurized hydrodynamic journal bearing is designed to support the bearing radially [3]. Counter rotor-tilting flow channels and fluidic interconnects are also incorporated into the two wafer pairs that cap the center wafer.

To simplify the nomenclature, we named the wafers in terms of functionality. As shown in figure 1, from top to bottom, they are called: forward foundation plate (FFP), forward endplate (FEP), rotor plate (RP), aft endplate (AEP), and aft foundation plate (AFP).

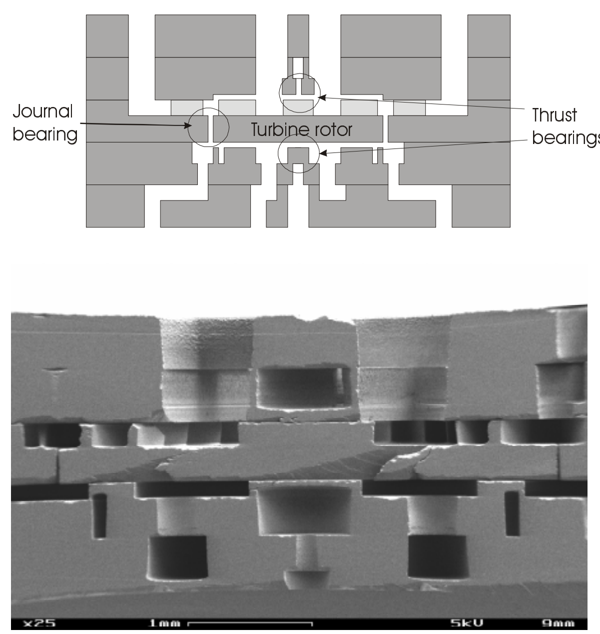


Figure 2 Schematic cross-sectional drawing indicating the location of the bearings and the SEM of the actual device cross-section.

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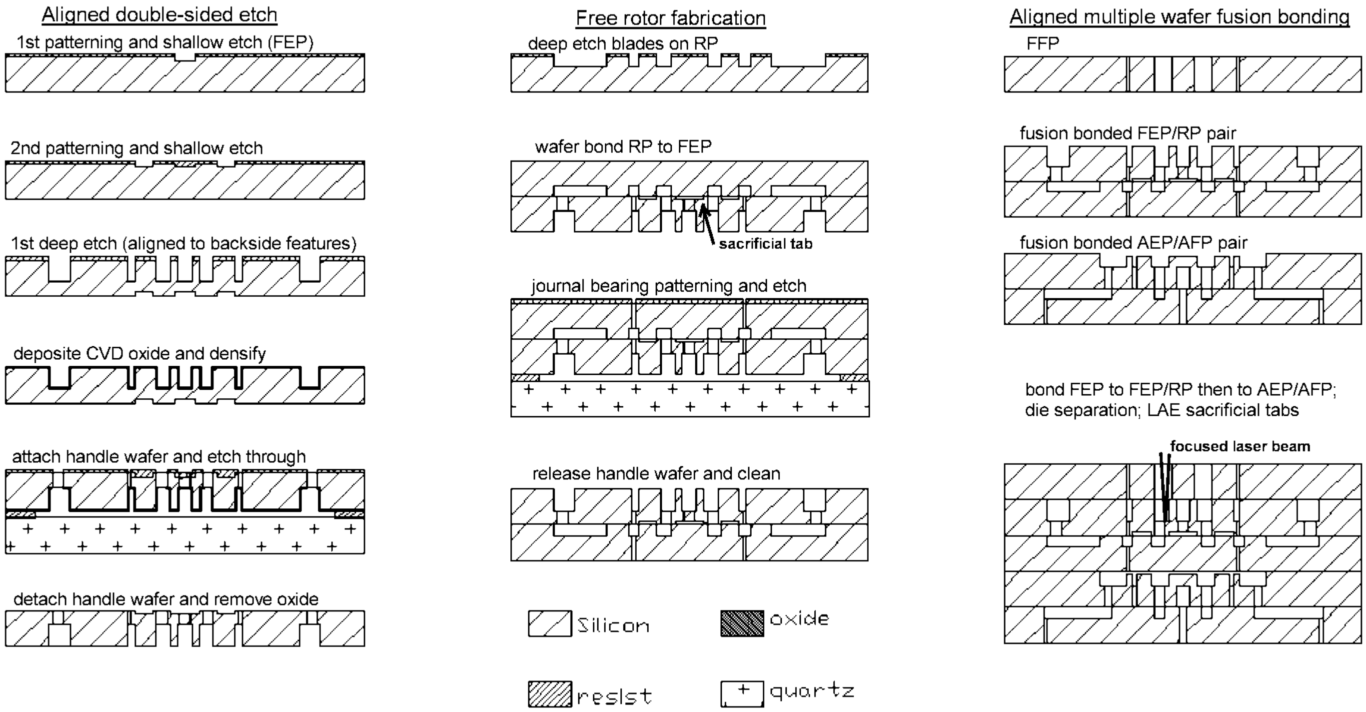



Figure 3 Fabrication process flow of the Micro Bearing Rig

## Process Flow

The device has been successfully fabricated, and was outlined in a late news poster at Hilton Head 98 [4]. The process flow involves the use of 16 masks, and 9 deep silicon etching steps on 5 wafers. A schematic illustration of the process is shown in figure 3. The fabrication starts by etching shallow global alignment marks on both sides of all wafers with the help of infrared alignment. Next, two shallow patterns are etched to depths of 1 μm and 4.5 μm, which define a thrust-bearing gap and blade clearance in a first wafer, called the forward endplate (FEP). This is followed by a deep silicon etch on the opposite side of the wafer to a depth of 350 μm. This deep etch process, first developed by Bosch, has been exhaustively characterized, and is reported elsewhere [5] [6]. Next, a sacrificial CVD oxide layer is deposited and densified on the deep-etched side to protect the surface from being attacked by the 2$^{nd}$ deep etch. Accordingly, the FEP wafer is inverted, a lithography operation is performed, and the wafer is reversably attached to a second quartz carrier wafer using a polymer bond. The purpose of adding a handle wafer is to prevent the wafer back-cooling Helium from leaking into the plasma chamber once the wafer is etched through. Thereafter, a 2nd deep etch is performed to etch through the wafer to the deep features on the front surface. After the etching, the handle wafer is released by 4:1 sulfuric acid/hydrogen peroxide mixture followed by an acetone rinse, and the device wafer is further cleaned by ashing. This FEP wafer is aligned fusion bonded to a second wafer, called the rotor plate (RP), which has been etched to a depth of 200 μm to define turbine blades and turbine inlet guide vanes. Following a critical photolithography step on the RP to

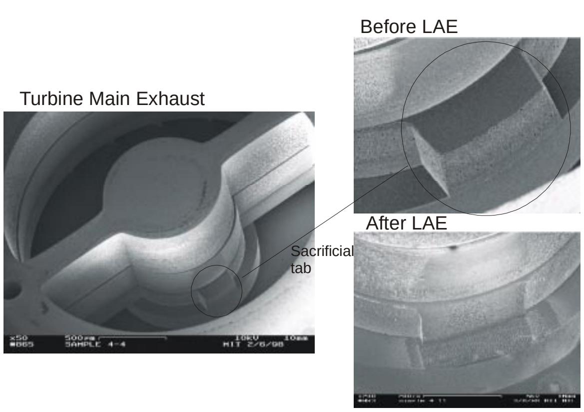
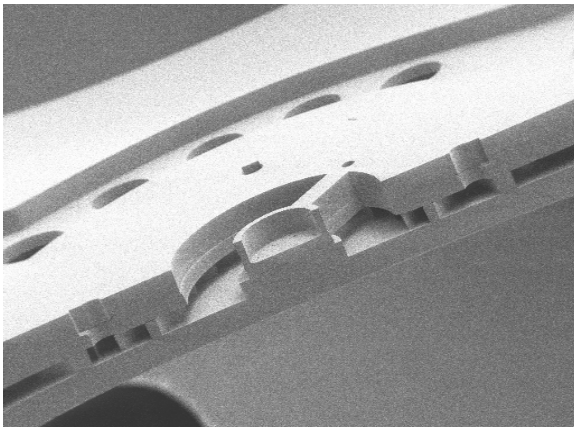
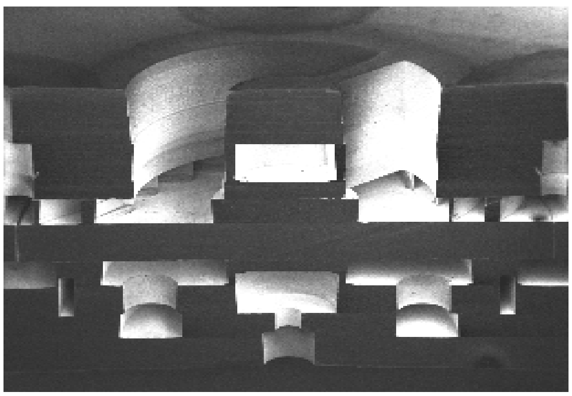



Figure 4 SEM looking into turbine main exhaust showing sacrificial tabs which holds the rotor in place before LAE. The close-ups show the tabs before and after removal.



(a)



(b)

Figure 5 (a) A bonded wafer pair of FEP and RP, prior to journal bearing etch. (b) Finished micro bearing rig.

define a journal bearing, the RP/FEP pair is again attached to a handle wafer, then deep etched to fully define the rotor.

In principle, the rotor is free at this point, however, sacrificial tabs have been created in the process of fabricating the FEP which bond to the rotor and hold it in place. These tabs are removed by laser-assisted etching after the final bonding, at which point the rotor is contained by the FEP and AEP. (Fig. 4)

The process proceeds with the fabrication of an aft endplate (AEP), which is similar in process to the FEP, and a forward foundation plate (FFP) and aft foundation plate (AFP), which provide fluidic interconnects. The AEP and AFP are aligned and fusion bonded together, after which this pair is bonded to the RP/FEP pair, and then bonded to the FFP, completing the stack. Two cross-sectional SEM micrographs of the device are shown in figure 5.

The bonded 5-wafer stack is sawed into 1.5 $cm^2$ dies and immersed in diluted HF to remove any surface oxide that will prevent proper etching during LAE. A focused argon laser beam then heats the sacrificial tabs, which hold the rotor, to near melting point in a chlorine flowing ambient. The heated silicon volume reacts with chlorine to form volatile silicon tetrachloride that is carried away by the flow [7]. The rotor is freed once the tabs are completely removed, and this completes the micro bearing rig fabrication process.

## Packaging and Instrumentation

Packaging is an important consideration during the design phase. Based on the experiences obtained during early prototype testing, o-rings are used to assure leakage-free fluidic connections. Considering the number of gas ports (13 total) that need to be connected and the minimum size of commercially available o-rings, we decided to compromise per-wafer yield and choose a large die size of 1.5 $cm^2$. As illustrated in figure 6, a three-piece aluminum/PMMA package is designed in consideration of die installation simplicity, visualization, and wafer thickness variation accommodation. This package has demonstrated leak-proof connections at gas feed pressures up to 125 psi.

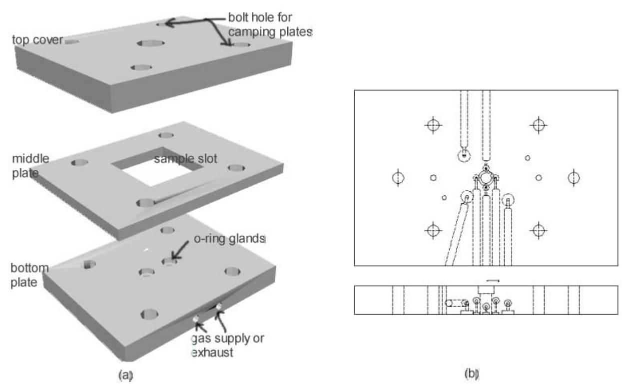



Figure 6 (a) Micro turbine/bearing packing concept illustration, the top and bottom plates are made of PMMA. (b) Layout of top packaging plate.

Although a device like the micro turbine seems like a perfect candidate for incorporating built-in micro sensors, the complicated fabrication process drove us from pursuing this approach immediately. Instead, a measurement subsystem consisting of seven pressure transducers, seven flow meters, and a fiber-optic speed sensor has been designed and built. (Fig. 7) Either independent or dependent flow control to each flow port could be enabled with a flexible flow control subsystem composed of a network of pressure regulators and metering valves. All the flow and pressure measurements are monitored and stored in a personal computer through a data acquisition card. Currently, we are also developing an infrared rotor position sensor that will provide detailed information about the rotor dynamics.

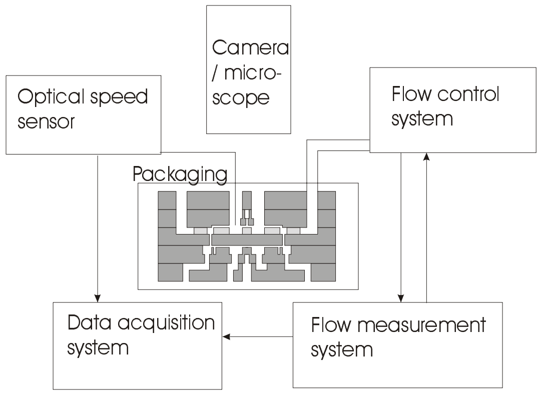



Figure 7  Micro rig testing system.

The fiber optic speed sensor is illustrated in figure 8. A diode laser shines on the top surface of turbine blades from a bare fiber probe. The height difference between blade top and root create an intensity variation in the reflection. As the rotor spins, a reflected optical pulse train is collected and transmitted through the coupler to a photo-diode and signal condition circuit. The amplified signal is directly fed to a spectrum analyzer and a high-speed data acquisition system that samples and stores at up to 1.25MHz. At the same time, a frequency to voltage converter with a bandwidth of 1MHz does real-time analysis.

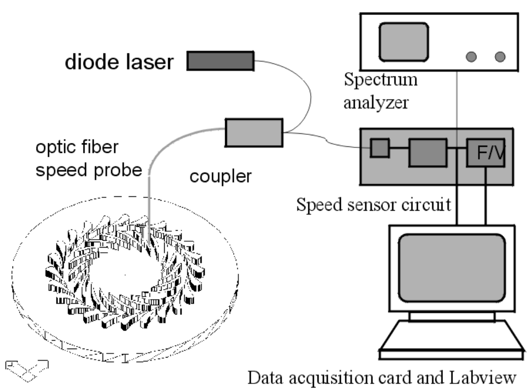



Figure 8  Micro turbine optical speed sensor.

## Experimental Results

The first process validation test is to measure the thrust bearing flow characteristics before and after the rotor is released by LAE. This test provides reference data for tuning a baseline model that is used for parametric study on bearing designs. It also serves as a fabrication yield characterization step because the flow rate of the bearing is directly related to the bearing gap, and the gap is defined by both the plasma etching and wafer bonding. As shown in figure 9, three dies out of twelve showed an unreasonable flow rate, illustrating a 25% yield loss after bonding.

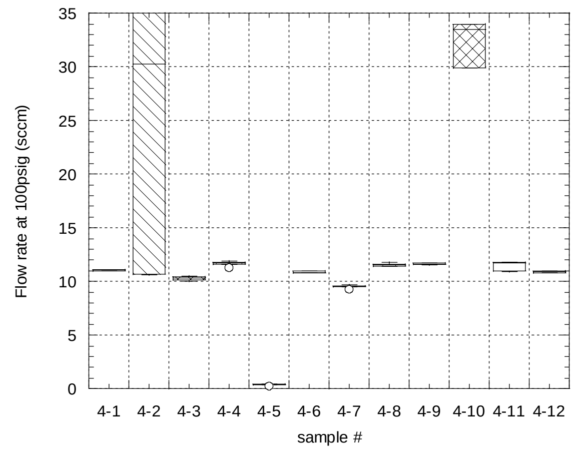



Figure 9  Cross wafer thrust bearing flow rate (yield) measurement. The flow rate is measured at 100 psig for all 12 devices across the wafer. Samples 4-2, 4-5, and 4-10 show results which are out of spec.

Figure 10 shows the pressure-flow characteristics of the nine device thrust bearings before LAE. The modeled flow is in good agreement with the data. After LAE, the rotor is displaced and the flow characteristics are measured again (Fig 11). The measured flow rate has increased, consistent with the increase in thrust bearing gap created by the measurement of the rotor.

During the spin test, the rotor is first axially supported by the thrust bearings. After axial balance is established, main turbine air is supplied to spin the turbine. Preliminary test results show continuous operation at up to 60,000rpm. Measurements on the current test rigs showed that the bearings were not built within the tight design specifications. With the as built dimensions, the bearing

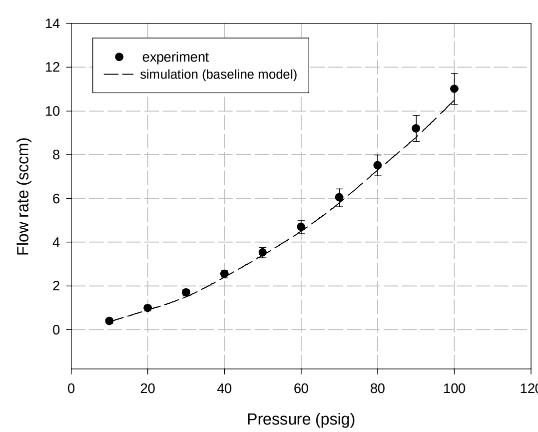



Figure 10  Pressure vs. flow of micro bearings before LAE rotor release.

model predicts low stiffness. This lack of stiffness results in a decreased capability to prevent the rotor from touching down, and could account for observed fluctuations of rotor speed. New bearing design and improvements in the process tolerances are in process that will result in higher stiffness bearings. These improvements should allow us to attain much higher rotation speed.

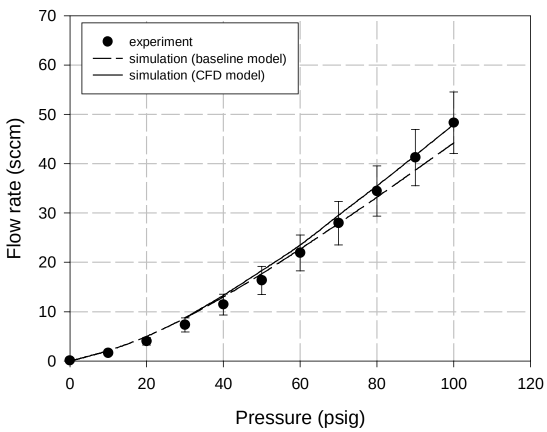



Figure 11 Experimental and simulation results for micro thrust bearings with maximum gap.

## Conclusion

The fabrication process flow described in this paper can be applied in many areas to build devices with complicated microfluidic interconnects. Data from the micro thrust bearings are useful for studying miniature fluidic floating devices. The micro rotary machinery will open new opportunities for fabricating micro valves, pumps, micro coolers, and micro propulsion devices.

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